Experimental Thermal and Fluid Science 84 (2017) 47–66

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Phase-resolved velocity flow fields induced by laboratory-generated plunging water waves

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ARTICLE INFO

Article history:
Received 12 August 2016
Received in revised form 5 December 2016
Accepted 19 December 2016
Available online 22 December 2016

Keywords:
Turbulence
Plunging wave
Cross correlation
Instantaneous velocity
Mean velocity
Phase
Velocimetry

ABSTRACT

Digital images of regular plunging water waves were captured by a camera and analyzed to examine the spatial and temporal evolution of phase-resolved instantaneous and ensemble-averaged velocity fields induced by the waves as they propagate and break in the surf zone of a laboratory flume. A computer-driven electronic measurement system was designed, developed and employed to capture images of the breaking waves as they propagate along a glass-walled laboratory flume and break on 1:20 plane slope. An 8-bit monochromatic, progressive scan digital camera was connected to the computer and mounted on the side of the flume to capture images of the breaking waves. Through the use of a trigger pulse from the wave generator, the computer synchronizes image acquisition by the camera at the instance the computer drives the strobe lights to illuminate the field of view. A full wave cycle of the breaking wave was too large to be imaged in one video frame, so the cycle was sub-divided into 20 overlapping phases. For a particular phase, 100 sequential image pairs were captured and saved on a computer. A digital correlation image velocimetry technique was later employed to calculate the spatial cross correlation of the gray scale image data by means of computing the cross-power spectrum of the Fourier transformed image samples. Displacements were measured to subpixel accuracy by interpolating the position of the cross-correlation peak. This gave a combined displacement of polystyrene particles and air bubbles entrained in the flow. One hundred instantaneous velocity flow fields were computed for each phase. Averaging data sets at each phase allowed an estimation of mean velocities at that phase. Structures of the velocity distributions are presented, both as vector fields and in the form of contours plots for phases where turbulence is predominant. Horizontal velocity is up to $2.32c$ while the vertical is $0.37c$, where $c = 1.08$ m/s is the wave phase velocity.

1. Introduction

Turbulent flows are fluid regimes characterized by chaotic, stochastic property changes, that include low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time. The study of turbulence is an inter disciplinary activity that has a wide range of applications such as: jet streams in the upper atmosphere, water currents below the surface of oceans, boundary layers growing on aircraft wings and breaking water waves. For breaking waves, as water waves approach shallow regions of the surf zone, they steepen until the crest becomes unstable and eventually breaks, resulting in air entrainment, energy dissipation, and the transfer of momentum to currents. The instantaneous velocity profile for such flows is one of the most fundamental quantities from which other turbulence parameters associated with the flow can be derived. Knowledge of velocity flow fields generated by breaking waves is of interest in linking fluid dynamical characteristics with complications associated with the flow. Velocity fields downstream of the breakpoint can reveal the location of high velocity gradients and recirculation areas as well as identification of zones of high velocity fluctuations. However, the main difficulty in measuring this quantity is the simultaneous presence in the fluid, of a large number of vortices with different characteristic sizes that mutually interact with each other as flow progresses. As a result, quantitative experimental measurements of the velocity profile of a turbulent flow has long been a demanding and challenging theme in fluid dynamics, fluid engineering, and other engineering fields concerned with fluid flow [1].

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http://dx.doi.org/10.1016/j.expthermflusci.2016.12.015
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Experimental approaches that use flow visualization techniques based on low-cost video recording and image processing systems have been adapted in some laboratories to provide quantitative flow information associated with breaking waves [2–6]. Some of the techniques that have been successfully adapted include laser Doppler velocimetry (LDV) and particle image velocimetry (PIV). LDV, however, is largely a single point measurement technique that does not provide information on the spatial structure of the flow, although simultaneous use of two or more systems can yield more information [7]. This technique gets overwhelmed by air bubbles near the crest, hence most previous studies using this technique were limited to determining fluid velocities below the trough region [8–10]. On the other hand, PIV technique a is non-intrusive whole-field optical method of flow visualization that enables the simultaneous measurement of velocities at many points in a fluid flow. PIV involves seeding the flow, illuminating the region under investigation and using a camera to capture two images of that region in rapid succession. Some researchers [11–14] used PIV but still could not map the velocity flow fields of the entire wave column because they again used laser light which could not provide information associated with the bubbly wave crest. The technique was also restricted to the region outside the aerated area, in general under the trough level or away from the breaking point. Using the PIV technique, Lin and Rockwell [15] were able to map the flow field directly beneath the spilling breaker, and were therefore able to show the existence of a shear layer beneath the breaking wave. Through further study, they were also able to characterize the evolution of wave breaking. Govender et al. [5] obtained comprehensive measurements of breaking waves using a technique similar to PIV. This technique, that was termed digital correlation image velocimetry (DCIV) extracts velocity information by measuring the combined displacement of polystyrene particles and air bubbles entrained by the breaking waves. The technique gave accurate, quantitative information about the flow field in terms of velocity vector plots and turbulence intensity. Ting and Nelson [16] measured instantaneous turbulent velocity field created by the breaking of spilling regular waves on a plane slope in a plane running parallel to the slope using particle image velocimetry. The measurement area encompassed the region where the large eddies generated at incipient wave breaking impinged on the bottom inside the surf zone. A total of 30 trials were conducted under identical experimental conditions. In each trial, six consecutive wave cycles were recorded. The measured velocity fields were separated into a mean flow and a turbulence component by ensemble averaging. The instantaneous turbulent velocity fields were analyzed to determine the occurrence frequency, location, geometry and evolution of the large eddies, and their contributions to instantaneous shear stresses, turbulent kinetic energy and turbulence energy fluxes.

Other researchers were successful in measuring the breaking wave flow field and the generated turbulence inside the aerated region [6,17]. This was however, accomplished for the less turbulent spilling water waves. Reported studies [5,6,18–26] successfully investigated fluid structures and the distribution of velocity in two-dimensional open channel flows. However, advances in the understanding of flow structure inside the highly aerated region of the flow such as the one created by plunging waves have not been adequately reported. As explained by Yeganeh-Bakhtiary et al. [27], this is mainly because plunging waves entrain large amounts of air bubbles in the swash and surf zones, making it difficult to optically measure velocity flow fields in the crest of the wave. A plunging wave breaks with more energy than a significantly larger spilling wave.

The purpose of this study was to perform experimental measurements to characterize the flow field in the flume immediately downstream of the breakpoint by mapping the velocity vector fields for a plunging breaker. We show how seed particle displacements were accurately measured using correlation of sequential digital images. Synoptic measurements of fluid velocities were made at five stations in the surf zone of the flume. Such experimental measurements and analysis generate large amounts of data and therefore to keep the number of pages reasonable, only selected experimental results from one station are presented herein. For this station, experimental results of the structures of the distributions and evolution of the velocity flow fields are presented for six phases around the crest, at which turbulence is predominant. The uniqueness of experiments reported here is that we were able to measure fluid velocities in the highly aerated crest region of plunging waves, which is normally difficult to experiment with because of the large amounts of air bubbles that make it difficult to optically access the flow.

2. Instrumentation and experimental setup

Experiments were conducted in a hired facility at the Coastal and Hydraulics Engineering Laboratory located at the Council for Scientific and Industrial Research (CSIR) in Stellenbosch, South Africa. It consists of glass-walled, rectangular flume, approximately 20 m long, 0.75 m wide and has a gentle beach slope of 1:20 which was chosen in order to get a long enough surf zone length over which measurements of wave parameters could later be conducted. In similar studies, other researchers [28–35] also used a 1:20 beach slope as the standard slope. The flume was filled with water to a depth of about 62 cm. Regular waves of 0.4 Hz frequency having a wave height 12 cm in the flat section of the flume were generated by a hydraulically driven, computer-controlled piston type wave maker manufactured by Wallingford [36]. This resulted in plunging waves that broke at a distance of about 4.0 m from the still water mark on the beach.

Fig. 1 shows the schematic diagram of the geometry of the laboratory flume used in this study. It illustrates characteristic regions of the flume, giving overall dimensions in addition to showing the sloping bottom and the coordinate system used. Coordinate x is directed parallel to the mean flow, and is conventionally established as positive if oriented onshore, with $x = 0$ at the intersection of the still water line (SWL) and the beach flow, a point 1.60 m from the break point towards the shore. y is perpendicular to the side wall so that the y-axis is set parallel to the shore with $y = 0$ at a lateral point 10 cm from the flume wall of the tank. z is the vertical coordinate with $z = 0$ at the SWL. The origin $(x, z) = (0, 0)$ is at the intersection of the beach slope and the still water level. With this convention, horizontal distances measured along the flume will be negative for positions away from the shore, towards the wave maker. Measurements were made at several stations along the flume, but results reported here were performed at the station marked, S, whose center is located 2.38 m from the still water mark on the beach.

Experimental setup and instrumentation that was developed and used for the acquisition of wave images is schematically shown in Fig. 2. The experimental setup consisted of a light source, mounted vertically above the flume section to be viewed. Mounted on the side of the glass flume was a charge-coupled device (CCD) Pulnix camera that was used to capture images of the breaking waves when the flow was illuminated by a pair of strobe lights. An 8-bit monochrome camera with a resolution of 752 × 468 pixels was used that operated in the non-interlaced mode. It has a built-in analog-to-digital and a digital-to-analog converters, providing both analog and digital outputs. In addition, it is equipped with an internal frame buffer, that allows the double acquisition so that the first image is quickly transferred into the buffer before readout, freeing the CCD for the next image. The camera shutter is kept open for the entire frame time, so although the CCD face-plate